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COST ESTIMATING RELATIONSHIPS FOR AIR AND SEALIFT MOBILITY FORCES

Norman J. Asher
William J. E. Shafer

March 1985

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Under Secretary of Defense for Research and Engineering

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SUMMARY

This document describes the development of cost estimating relationships (CERs) for cargo aircraft and the different types of ships used by U.S. and USSR mobility forces. Both RDT&E and procurement cost CERs are presented for cargo aircraft, but only procurement cost for ships (because RDT&E costs for non-combatant ships are relatively minor and are usually embedded in the procurement cost of the ships). The principal purpose for the derivation of these particular CERs is to estimate the costs of the USSR and the U.S. mobility systems in the same consistent manner for relative comparisons, a basic premise in their development being that they contain only those input values and/or parameters that could be estimated based on observable characteristics of USSR systems.

PREFACE

This memorandum report is part of a broader continuing program at the Institute for Defense Analyses under the technical cognizance of Dr. Paul J. Berenson, Special Assistant for Assessment, Office of the Under Secretary of Defense for Research and Engineering, under Task T-3-150, dated 23 December 1982. The broader effort, "NATO/Warsaw Pact Acquisition Balance," has as its purpose the development of an overview of the U.S./USSR technology and acquisition balance.

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TABLES

FIGURES

DEVELOPMENT OF COST ESTIMATING RELATIONSHIPS

This document describes the development of cost estimating relationships (CERs) for cargo aircraft and the different types of ships used by U.S. mobility forces. Both RDT&E and procurement cost CERs are presented for cargo aircraft, while only procurement cost CERs are presented for ships. RDT&E costs for non-combatant ships are relatively minor and are usually embedded in the procurement cost of the ships.

The sole purpose for the derivation of these particular CERs is to estimate the costs of the USSR and the U.S. mobility systems in the same consistent manner for relative comparisons. Therefore, a basic premise in the development of these CERs must be that they use only input values and/or parameters that can be estimated or observed for USSR systems. Since the limited use of the outputs of these analyses was the development of long term trends over time between the two countries, the degree of sophistication in the development of these CERs was felt to be quite satisfactory.

A. CARGO AIRCRAFT

Aircraft characteristics and flyaway[1] and RDT&E costs were collected for nine historical U.S. military cargo aircraft programs. Cost data from several sources were collected and normalized for quantities of aircraft and to constant year dollars. A "best estimate" cumulative average cost for 100

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[1]Flyaway cost is used as a generic term related to the creation of a usable end item of hardware. It includes basic structure/airframe, propulsion, electronics, and government furnished equipment (GFE).

aircraft was developed for each aircraft. Finally, the theoretical first unit flyaway cost was derived based on an assumed 85 percent cumulative average learning curve. The results are presented in Table 1. As can be seen, the piston-powered aircraft were all placed in service during the 1949-1955 period, while the turbine-powered aircraft entered service between 1957 and 1970. Turbine-powered aircraft had considerably higher costs than piston-powered aircraft of similar weight, as would be expected since turbine-powered aircraft represent a higher level of technology and fly at approximately twice the speed of the piston-powered generation of aircraft. Accordingly, it was decided to develop two sets of CERs--one for piston-powered and one for turbine-powered aircraft.

It was not considered necessary to include the initial operational capability (IOC) year in the piston-powered aircraft CERs since those aircraft were all introduced within a six-year

Table 1. DATA FOR DERIVATION OF TRANSPORT AIRCRAFT COST ESTIMATING RELATIONSHIPS

Aircraft	Empty Weight (Thous. Lb.)	IOC Year	Theoretical First Unit Flyaway Cost (Million 1986 $)	RDT&E Cost (Million 1986 $)
Piston-Powered				
C-119	40	1949	13.0	85
C-123	31	1955	11.7	76
C-124	101	1950	33.5	217
C/KC-97	88	1949	32.6	212
Turbine-Powered				
C-130	59	1957	41.1	346
C-141A	134	1965	124.2	668
C-5A	321	1970	409.7	3,246
C-133	117	1958	101.2	539
C/KC-135	98	1957	99.3	527

period and represented approximately the same level of technology. The IOC year was included in some of the turbine-powered CERs, but the relationship for one of them was counterintuitive; i.e., it indicated a decrease in cost with IOC year. Accordingly, the CERs selected use only empty weight as the explanatory variable.

The flyaway CERs are:

Piston-Powered:

$$FC = 0.389(WT)^{0.975}$$

Turbine-Powered:

$$FC = 0.1925(WT)^{1.328}$$

where

FC = First unit flyaway cost in millions of FY 1986 dollars

WT = Empty weight in thousands of pounds.

The first unit flyaway cost estimates based on these equations agree quite well with the observed values (see Figures 1 and 2). Figure 3 shows the relationship of the estimated to observed first unit flyaway costs for both piston-powered and turbine-powered engine aircraft.

The RDT&E costs are less reliable than the flyaway costs because most of the aircraft were developed prior to the institution of the Five Year Defense Program (FYDP) in FY 1962. Prior to the FYDP, much of what is presently included in RDT&E costs in the FYDP was paid for out of procurement funds. There was some separation of development costs, but they are difficult to identify and also difficult to obtain because they are so old. Some RDT&E costs were obtained for the turbine-powered aircraft which seem reasonable, but reliable data for the piston-powered aircraft could not be obtained. Accordingly, a median ratio (6.5) of RDT&E to first unit flyaway cost for the turbine-powered aircraft was developed and used to derive the RDT&E costs in Table 1 for the piston-powered aircraft.

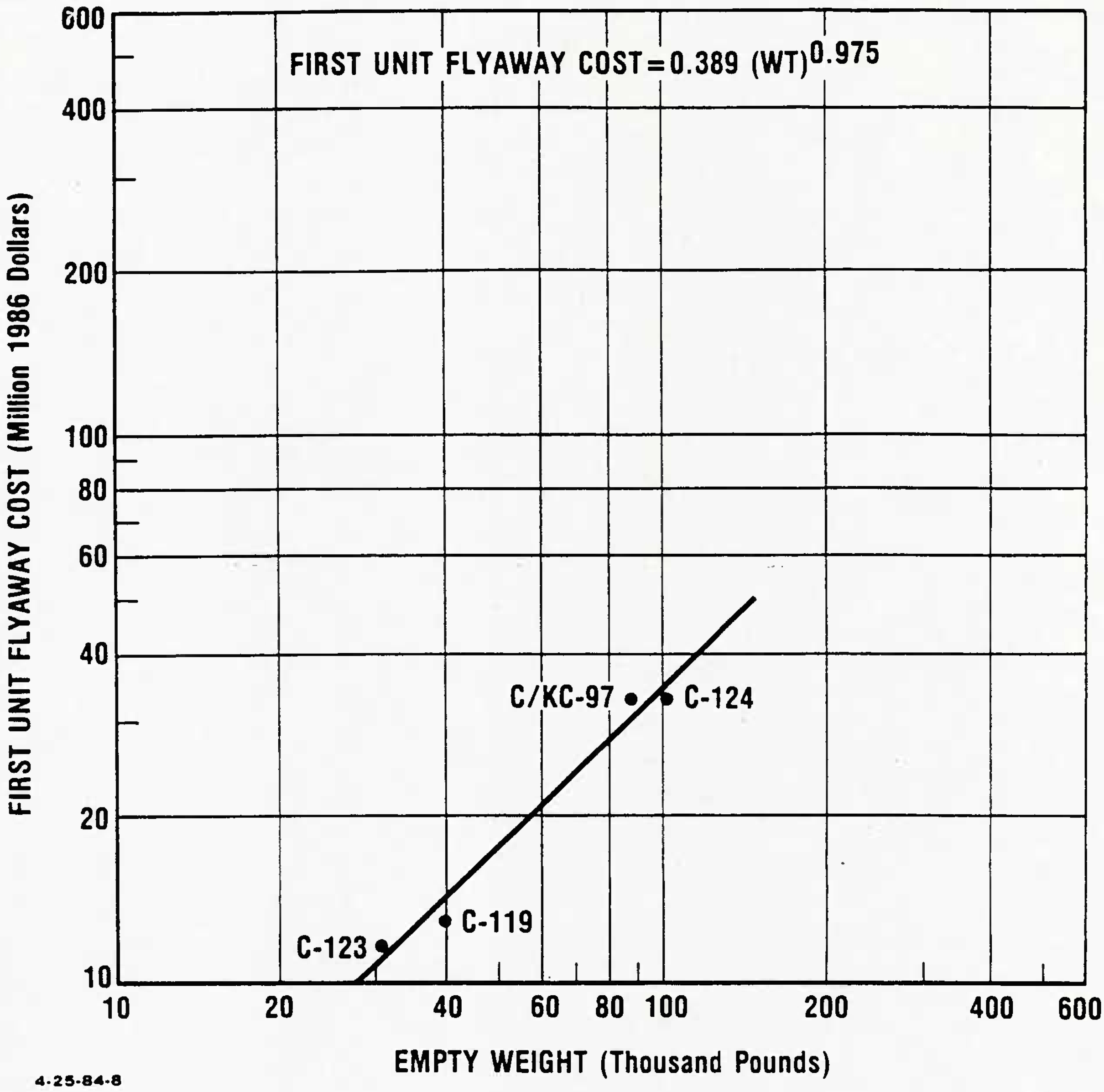

Figure 1. PISTON-POWERED CARGO AIRCRAFT FIRST UNIT FLYAWAY COST (In Millions of FY 1986 Dollars)

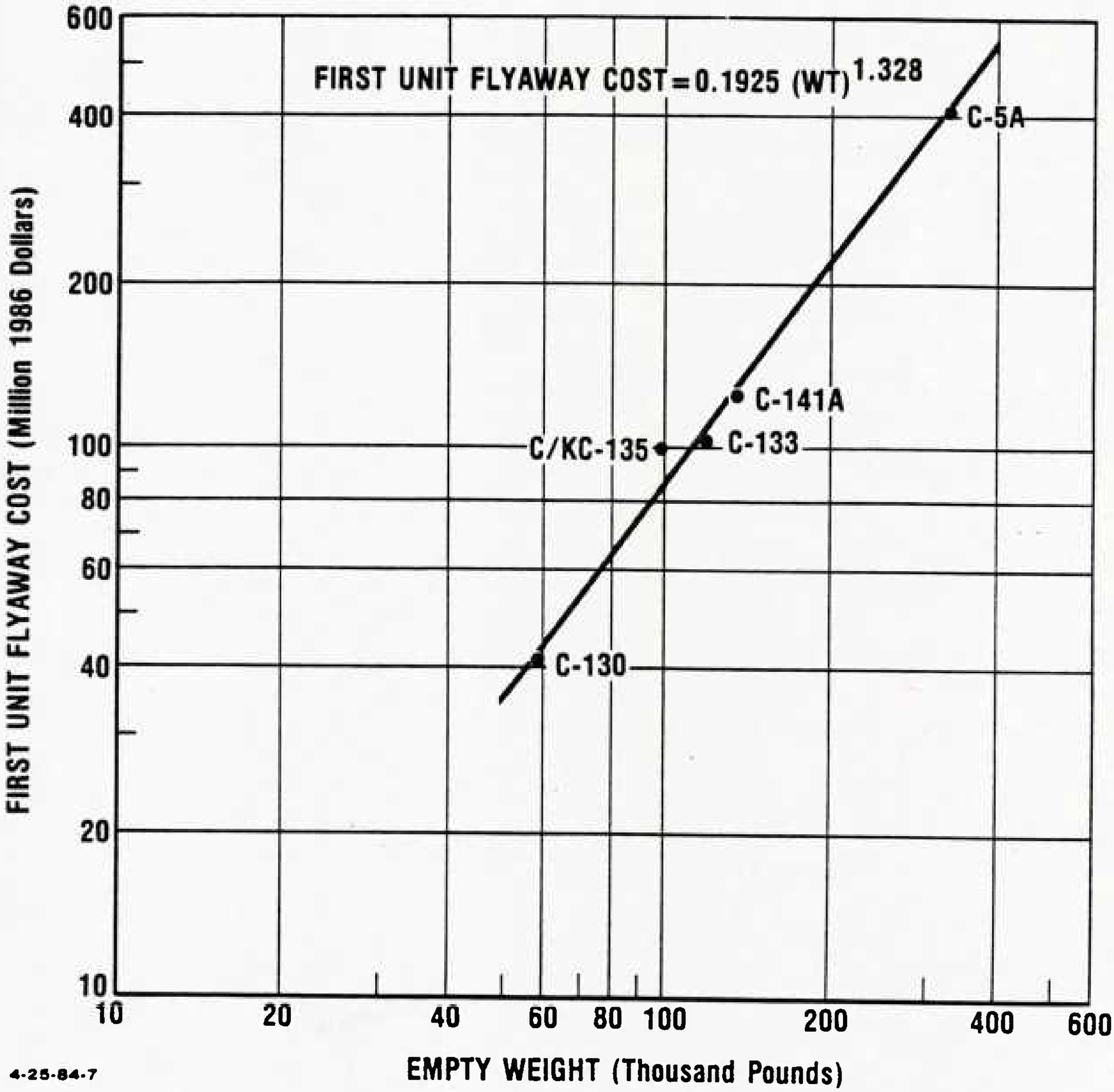

Figure 2. TURBINE-POWERED CARGO AIRCRAFT FIRST UNIT FLYAWAY COST (In Millions of FY 1986 Dollars)

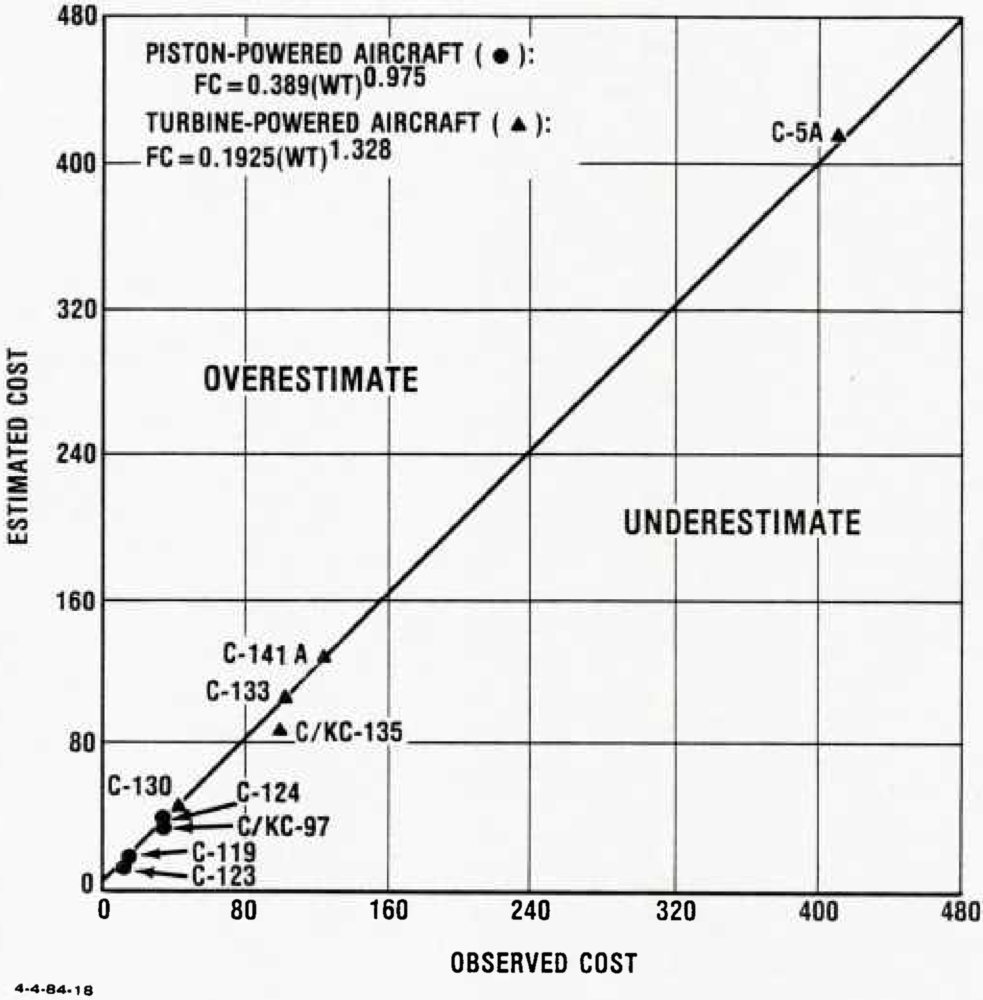

Figure 3. ESTIMATED VERSUS OBSERVED FIRST UNIT FLYAWAY COST OF U.S. CARGO AIRCRAFT (In Millions of FY 1986 Dollars)

The RDT&E CERs are:

Piston-Powered:

$$RC = 2.56(WT)^{0.971}$$

Turbine-Powered:

$$RC = 1.071(WT)^{1.355}$$

where

RC = RDT&E cost in billions of FY 1986 dollars

WT = Empty weight in thousands of pounds.

The RDT&E cost estimates based on these equations agree reasonably well with the observed values (See Figures 4 and 5). Figure 6 shows the relationship of the estimated to observed RTD&E costs for both piston-powered and turbine-powered cargo aircraft.

Some U.S. military aircraft have been procured as follow-on military production to on-going commercial programs (i.e., the C-118 version of the DC-6, the C-121 version of the Constellation, and the KC-10 version of the DC-10). Integration of commercial and military aircraft cost and price data is complicated because of the different relationships between cost and price that generally occur in the civilian and defense marketplaces. In military aircraft procurements, there is generally a direct correlation between marginal cost and marginal price, while in commercial aircraft programs prices tend to be fixed over large production quantities, even though the marginal production costs may be falling. The relationship between cost and price for commercial and military aircraft programs is conceptually illustrated in Figure 7. In commercial programs, the selling price is approximately constant (in real terms) over an extended period of the program. Initially, the company loses money while the selling price does not cover costs, and later the company makes money when the selling price is greater than costs. The manufacturer is forced to sell the early production aircraft below cost because no airline would volunteer

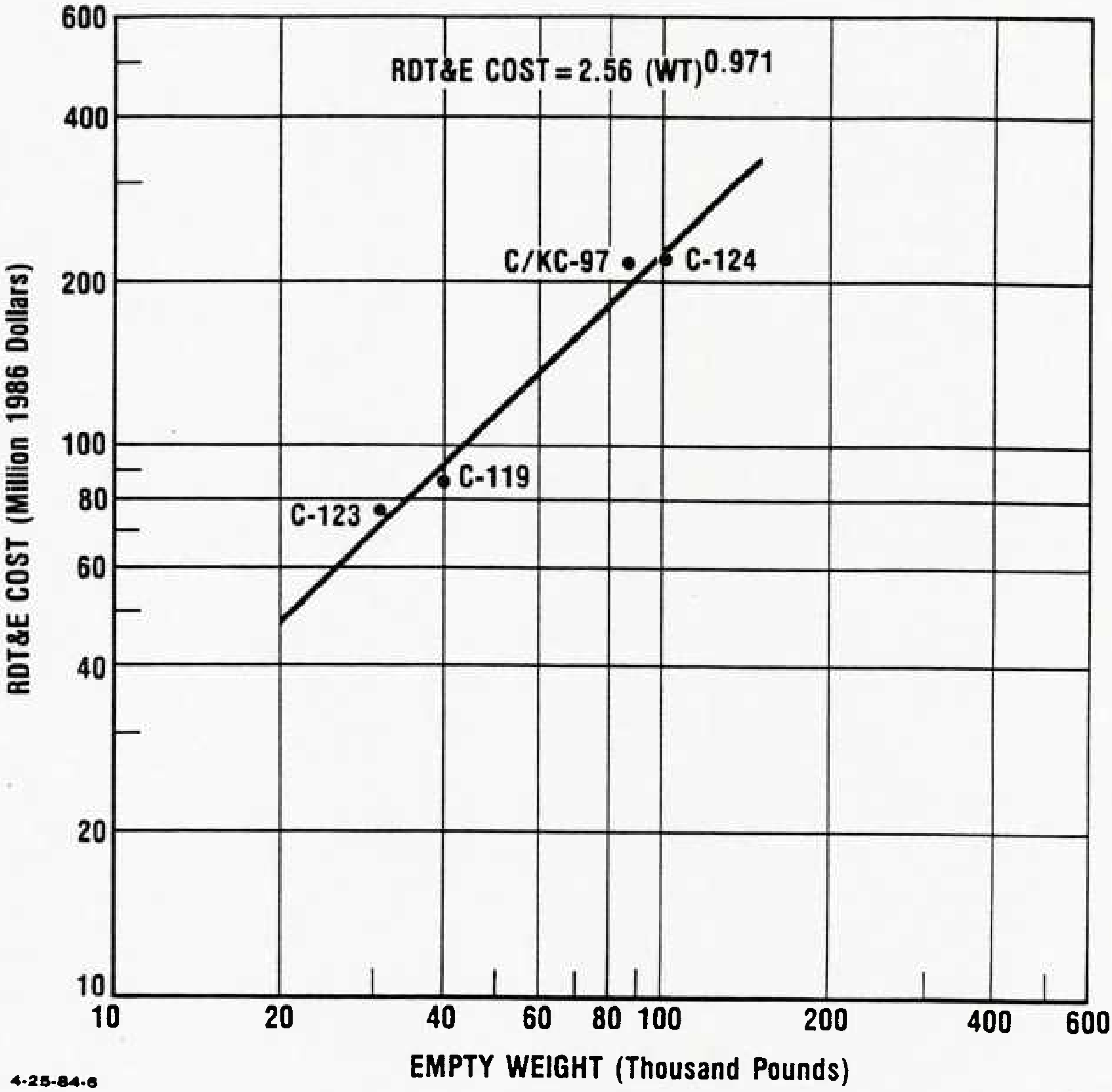

Figure 4. PISTON-POWERED CARGO AIRCRAFT RDT&E COST (In Millions of FY 1986 Dollars)

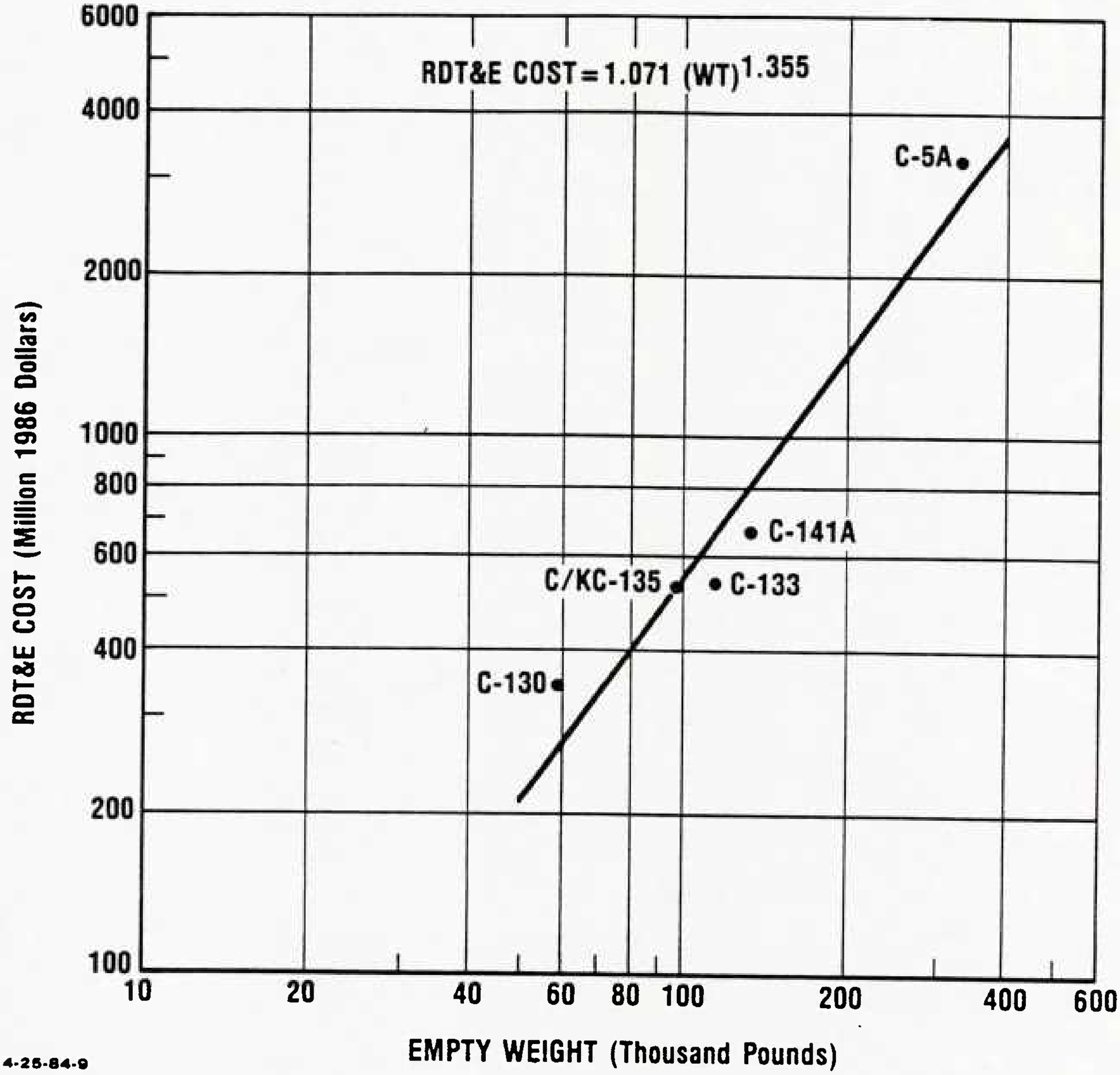

Figure 5. TURBINE-POWERED CARGO AIRCRAFT RDT&E COST (In Millions of FY 1986 Dollars

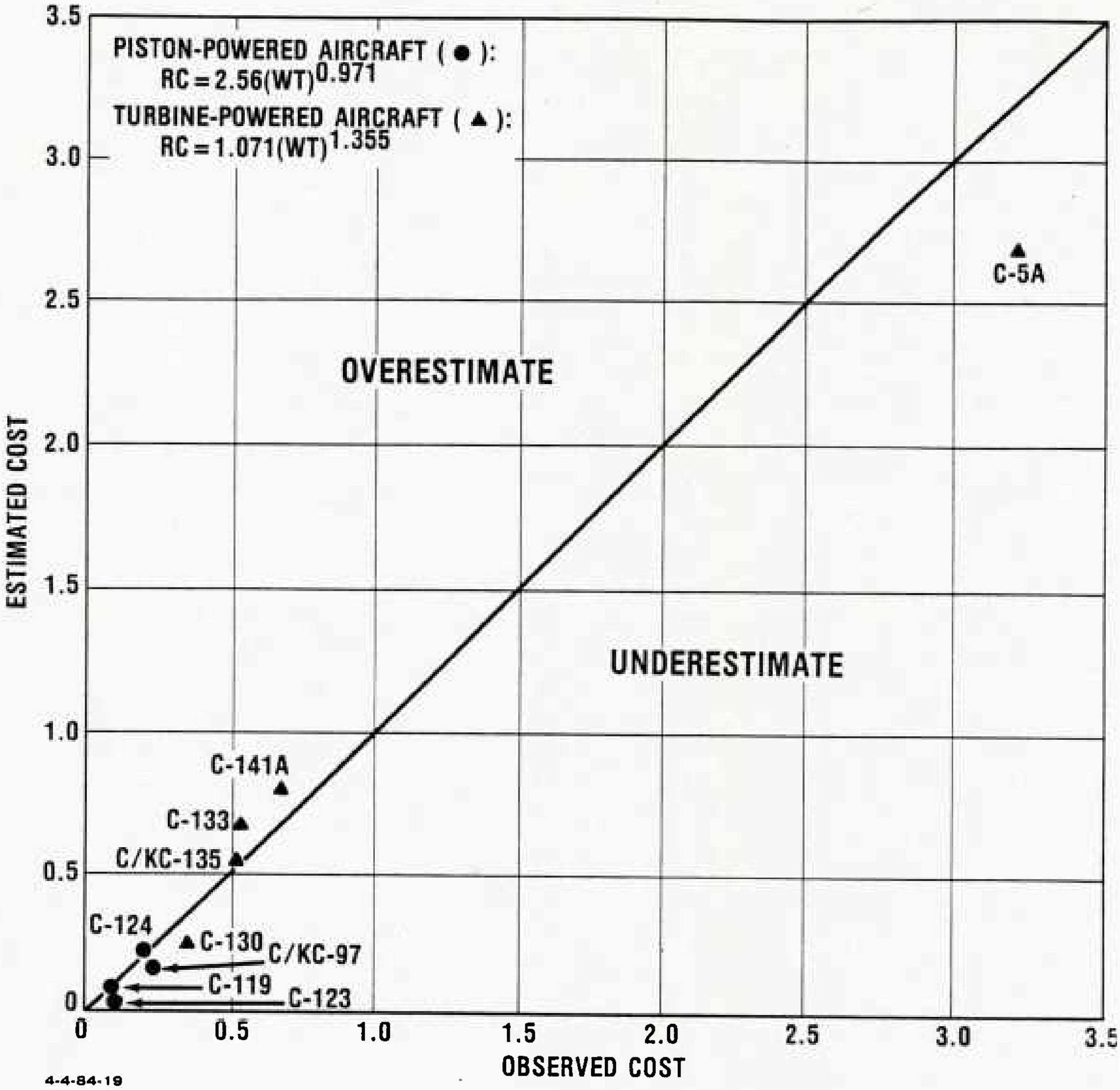

Figure 6. ESTIMATED VERSUS OBSERVED RDT&E COST OF U.S. CARGO AIRCRAFT (In Billions of FY 1986 Dollars)

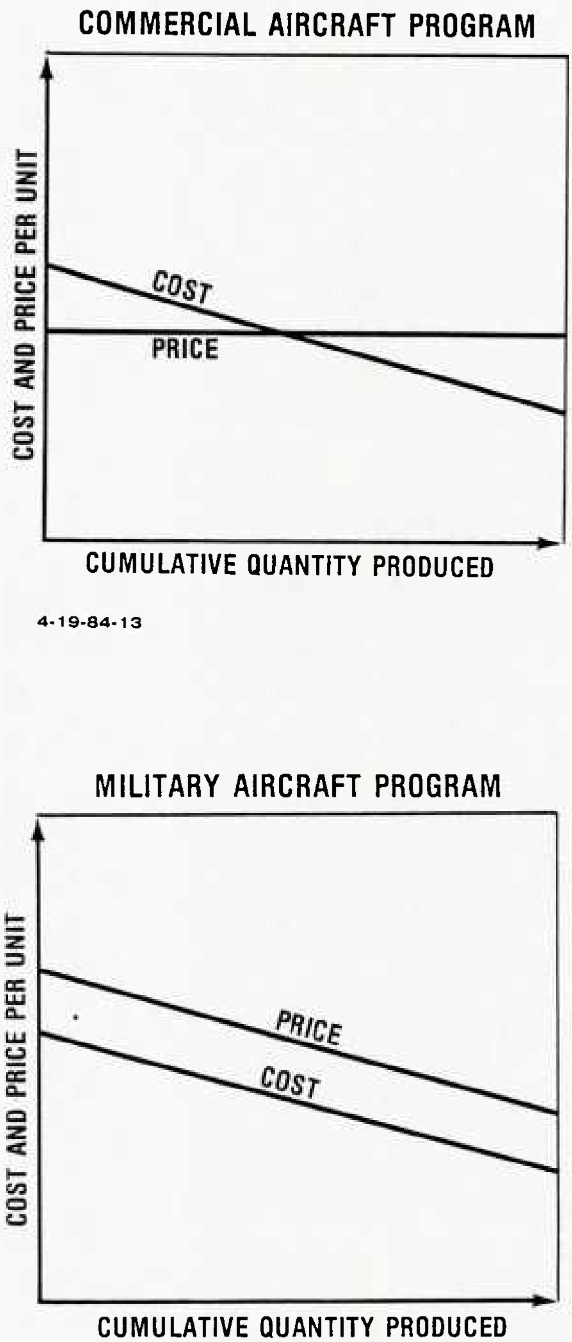

Figure 7. RELATIVE COSTS AND PRICES FOR COMMERCIAL AND MILITARY AIRCRAFT PROGRAMS

to buy first and pay a higher price than its competitors who would buy later. In the case of a military program, the government usually buys in yearly increments and pays a price that covers costs and provides a profit to the company.

Because of these differences in the pricing of commercial and military programs, it was felt that the costs to the military of aircraft procured as follow-on military production to on-going commercial programs would not be directly comparable to pure military aircraft programs; therefore they were not included in the data base from which the CERs were developed. However, the CERs will be used to estimate the costs of these combined commercial/military programs. There are a number of these programs in the USSR forces as well where the same basic aircraft are used by Aeroflot and the USSR military mobility forces.

B. SEALIFT SHIPS

The ships that comprise the sealift mobility forces, as historically and currently constituted, were organized into six categories for the purposes of deriving CERs. They are (1) passenger ships/transports, (2) dry cargo ships, (3) roll-on/roll-off ships, (4) container ships, (5) tankers, and (6) barge carrying ships. Many ships in the Military Sealift Command (MSC) active fleet in 1965 and subsequent years were built during World War II; therefore, historical cost data and characteristics on these ships dating back to 1941 were collected.

The ships comprising the mobility forces are merchant ships or ships of a merchant design that have been modified for a specific function. CERs developed for these ships were based upon a cost-to-weight relationship. The weight used to derive CERs for combatant ships is typically a displacement tonnage, i.e., light or full load displacement. Light displacement is the weight of the ship excluding cargo, fuel, ballast, stores, passengers, and crew, but with water in boilers to the steaming level. Full load

displacement is the weight of the ship including all the foregoing exceptions and all other items necessary for a voyage, which brings the ship down to load draft. For commercial ships, generally only two forms of tonnage are readily available: gross tonnage and deadweight tonnage. Gross tonnage is a measure of the entire cubic capacity of a ship where 100 cubic feet equals one ton, except for certain spaces which are exempt; e.g., water ballast tanks, and spaces above the uppermost continuous deck. Deadweight tonnage is the total lifting capacity of the ship expressed in tons of 2,240 pounds. A series of regressions were run relating procurement cost to both gross and deadweight tonnage. The procurement cost/gross tonnage regressions produced the better set of CERs.

To provide a larger number of data points upon which to derive CERs, historical data were collected on merchant ships constructed in the United States and delivered between January 1941 and January 1984 and aggregated into the six ship categories. Within each ship category, ships of a similar type and/or tonnage were aggregated to form a single data point. Table 2 displays both the data used in developing the CERs and the results of comparing the CER-estimated cost to the observed cost. A comparison of the total estimated cost to the total observed cost is made for each category and the result is in the total line of the percentage difference.

The percentage difference for five of the six ship categories is less than 12 percent. The difference for the dry cargo ship category is 34.5 percent when the C2 (Liberty) ship data is included in the regression. This large difference is driven by the C2 (Liberty) ship entry in which the sample size (2,578 ships) is over six times as large as the next largest sample. These ships were mass produced during World War II under conditions radically different from shipbuilding since World War II; therefore, the average procurement cost for the

Table 2. COMPARISON OF OBSERVED AND ESTIMATED SHIP PROCUREMENT COSTS (Millions of FY 1986 Dollars)

Ship Category	Average Gross Tons	Number of Ships	Average Observed Cost	Total Observed Cost	Average Estimated Cost	Total Estimated Cost	Percent Difference
Passenger Ships/ Transports							
C4-S-A1	13,000	30	132.9	3,987.0	158.4	4,752.0	16.0
P2-S1-DN1	13,319	3	209.2	627.6	160.8	482.4	-30.1
P2-S2-9,11A	15,178	4	197.3	789.2	174.8	699.2	-12.9
P-2-SE2-R1	15,993	8	165.8	1,326.4	180.9	1,447.2	8.3
P2-S2-R2	17,851	11	142.8	1,570.8	194.9	2,143.9	26.7
P3-S2-DL2	23,719	2	261.1	522.2	238.9	477.8	- 9.3
Total				8,823.2		10,002.5	11.8
Dry Cargo Ships							
C1-M-AV1	3,806	218	29.8	6,496.4	36.8	8,022.4	19.0
C2 (Liberty)[1]	7,187	2,578	24.8				
C2 (Victory)	7,608	414	31.7	13,123.8	49.9	20,658.6	36.5
C3-S-A2	7,857	59	45.2	2,666.8	50.8	2,997.2	11.0
C3 (post WW II)	9,658	54	75.2	4,060.8	57.0	3,078.0	-31.9
C4	11,216	108	85.5	9,234.0	62.4	6,739.2	-37.0
C5-S-75A	21,590	5	87.7	438.5	98.1	490.5	10.6
Total				36,020.3		41,985.9	14.2
Roll-on/Roll-off Ships							
C3-ST-14A	12,750	1	93.6	93.6	95.0	95.0	1.5
Undesignated	14,400	3	92.7	278.1	98.9	296.7	6.3
Undesignated	15,078	10	103.5	1,035.0	100.5	1,005.0	- 3.0
C4-ST-67A	16,467	1	125.2	125.2	103.8	103.8	-20.6
Undesignated	18,000	1	87.1	87.1	107.4	107.4	18.9
C7-S-113A	18,500	3	107.6	322.8	108.6	325.8	0.9
Undesignated	20,000	2	117.3	234.6	112.1	224.2	- 4.6
Total				2,176.4		2,157.9	- 0.9
Container Ships							
Undesignated	4,000	2	28.2	56.4	62.6	125.2	54.9
C7-S-68C/D	11,400	5	112.4	562.0	76.3	381.5	-47.3
C5-S-73B	13,000	3	75.7	227.1	79.3	237.9	4.4
C5	17,000	5	69.6	348.0	86.7	433.5	19.6
C7-S-68E	18,000	2	71.3	142.6	88.5	177.0	19.4
C6-S-85A	18,700	4	94.7	378.8	89.8	359.2	- 5.4
C7	19,700	1	78.9	78.9	91.6	91.6	13.9
C6-S-85B	21,470	4	97.5	390.0	94.9	379.6	- 2.6
Undesignated	23,000	1	129.1	129.1	97.8	97.8	-32.0
C7-S-88A	23,740	3	113.0	339.0	99.1	297.3	-14.0
Undesignated	27,000	2	99.3	198.6	105.2	210.4	5.6
C8-S-85D	31,430	2	168.2	336.4	113.3	226.6	-48.3
C9-S-132B	40,490	3	77.5	232.5	130.1	390.3	40.4
Total				3,419.4		3,407.9	- 0.3

[1]This entry was not used in the development of the CER, included for information only.

Table 2. (continued)

(Millions of FY 1986 Dollars)

Ship Category	Average Gross Tons	Number of Ships	Average Observed Cost	Total Observed Cost	Average Estimated Cost	Total Estimated Cost	Percent Difference
Tankers							
Tankers are not designated as to hull type.	4,950	2	11.5	23.0	22.7	45.4	49.3
	6,500	1	22.7	22.7	27.8	27.8	18.3
	10,843	7	56.7	396.9	42.2	295.4	-34.4
	11,414	7	56.2	393.4	44.1	308.7	-27.4
	12,467	3	53.1	159.3	47.6	142.8	-11.6
	15,320	3	58.3	174.9	57.0	171.0	- 2.3
	16,102	11	66.2	728.2	59.6	655.6	-11.1
	17,300	17	59.5	1,011.5	63.6	1,081.2	6.4
	18,581	31	69.5	2,154.5	67.8	2,101.8	- 2.5
	19,111	9	72.5	652.5	69.6	626.4	- 4.2
	20,383	24	75.9	1,821.6	73.8	1,771.2	- 2.8
	21,000	11	66.6	732.6	75.8	833.8	12.1
	22,338	8	66.5	532.0	80.2	641.6	17.1
	23,443	14	82.7	1,157.8	83.9	1,174.6	1.4
	24,500	2	66.9	133.8	87.4	174.8	23.5
	25,500	2	96.3	192.6	90.7	181.4	- 6.2
	26,000	1	95.6	95.6	92.4	92.4	- 3.5
	27,000	6	96.9	581.4	95.7	574.2	- 1.3
	28,483	6	86.1	516.6	100.6	603.6	14.4
	29,000	2	106.7	213.4	102.3	204.6	- 4.3
	30,000	18	108.1	1,945.8	105.6	1,900.8	- 2.4
	31,000	5	97.3	486.5	108.9	544.5	10.7
	32,000	3	139.9	419.7	112.2	336.6	-24.7
Total				14,546.3		14,490.2	- 0.4
Barge Carrying Ships							
C8-S-82A	20,500	3	147.0	441.0	104.3	312.9	-40.9
C8-S-81B	26,400	11	105.7	1,162.7	117.0	1,287.0	9.7
C9-S-81D	32,325	9	97.3	875.7	129.8	1,168.2	25.0
Total				2,479.4		2,768.1	10.4

C2 (Liberty) ships is lower than all other ships in the dry cargo ships category. Because of these factors the C2 (Liberty) ships were dropped from the data base and a new CER was derived. This CER reduced the dry cargo ship category error from 34.5 percent to 14.2 percent, and the average absolute error decreased about one percent.

Another attempt was made to improve the fit of the regression line to the data for dry cargo ships using a least squares fit to minimize the percentage deviation. A power form equation was used to perform the percentage deviation minimization. The results were mixed. The category error was reduced about 5 percent, but the average absolute error increased by about 1.6 percent.

Other data sources examined as possible inputs to the development of CERs were ship speed and horsepower. Neither of these characteristics proved useful; thus, they were dropped from further analysis.

Light weight displacement tonnage for U.S. container ships was obtained and a CER was derived to determine how it would compare with the CER using gross tonnage. The result was an increase in the category error of about 2 percent and a decrease in the average class absolute error of about 13 percent. Discussion with personnel at the Naval Operational Intelligence Center (NOIC) affirmed that light displacement data for Soviet ships is not available; therefore, CERs based on light displacement cannot be used in the U.S.-Soviet comparisons even if they could be obtained for all U.S. ship categories. Personnel at NOIC said that gross and deadweight tonnage were available and were used by them in their work. In view of this information, no further CER analysis was attempted.

A CER for the barge carrying ships using the three cost/gross tonnage data points was unreasonable because it would indicate

that cost varies inversely with tonnage. Therefore the centroid of the three data points was determined and related to the slopes of the CER curves for roll-on/roll-off ships and container ships. These two types of ships were selected as being most similar in design and construction to barge carrying ships. A linear curve was constructed for the barge carrying ships using as its origin the midpoint between the origins of the curves for the roll-on/roll-off ships and container ships and passing through the centroid of the barge carrying ships. The CER was determined from the slope of the curve.

Table 3 presents, for each ship category, a linear CER, the error range, and the average absolute error. From this table the reader can obtain an appreciation for the fit of the CERs to the data. Even numbered Figures 8 through 16 display the observed procurement cost versus gross tonnage of the ships within each ship category and the linear CER curve resulting from the regression. Figure 18 displays the observed procurement cost versus gross tonnage for barge carrying ships for which a CER was constructed. Odd numbered Figures 9 through 19 display the goodness of fit of the data.

Table 3. SHIP CATEGORY COST ESTIMATING RELATIONSHIPS

Ship Category	CER	Error Range (% to %)	Average Absolute Error (%)
Passenger Ships/Transports	C = 60.8+7.51Tg	30.1 to -26.8	17.2
Dry Cargo Ships	C = 23.7+3.45Tg	36.5 to -37.0	24.3
Roll-On/Roll-Off Ships	C = 64.9+2.36Tg	20.4 to -18.9	7.9
Container Ships	C = 55.2+1.85Tg	48.3 to -54.9	23.7
Tankers	C = 6.3+3.31Tg	34.8 to -49.6	12.7
Barge Carrying Ships	C = 60+2.16Tg	42.7 to -32.5	25.2

Figure 20 displays the CER curves for the six categories of ships. The slopes of the curves for tankers and dry cargo ships are similar as are the slopes of the curves for container ships and roll-on/roll-off ships. The barge carrying ships curve was derived from the curves for the container ships and the roll-on/roll-off ships. The passenger ships/transports curve rises more rapidly as gross tonnage increases than any of the other curves. Inituitively this appears reasonable as passenger ships are more costly to construct due to the large number of compartments in these ships.

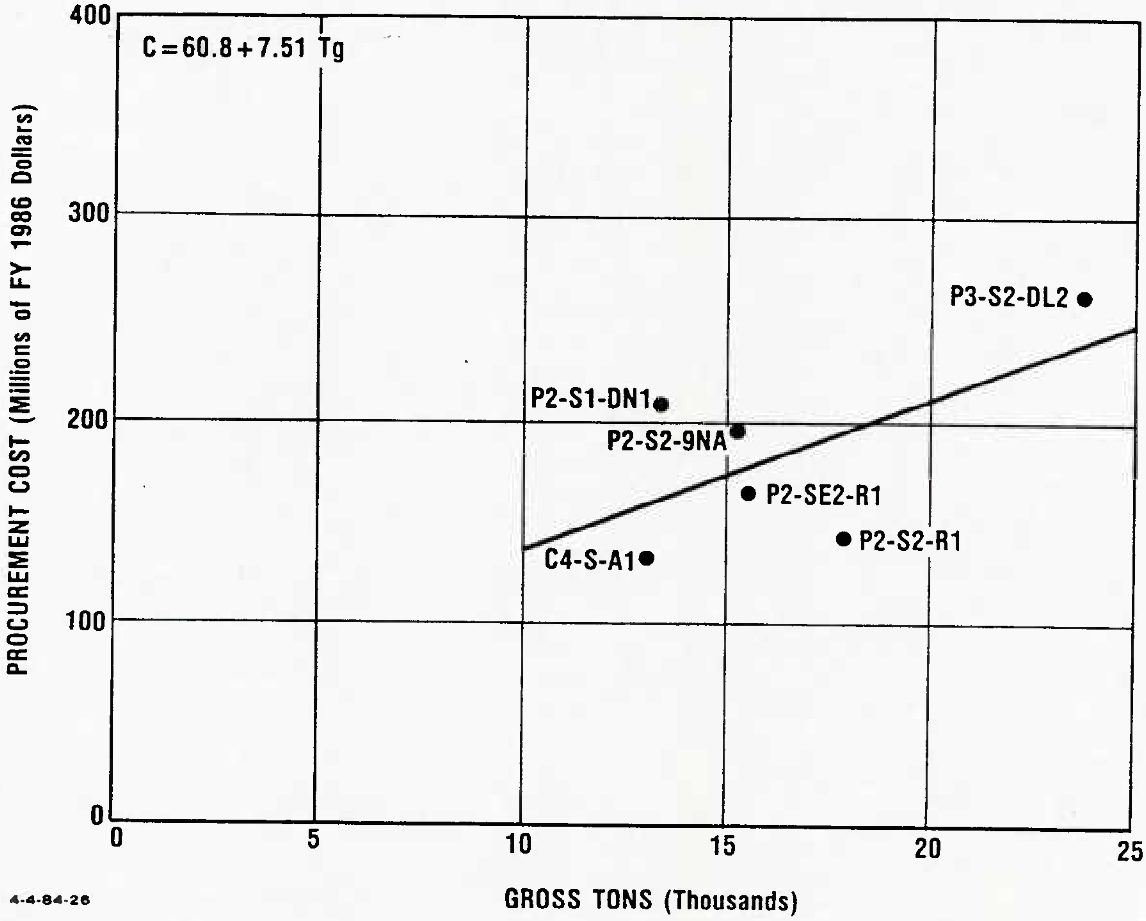

Figure 8. PROCUREMENT COST VERSUS GROSS TONNAGE CURVE FOR PASSENGER SHIPS/TRANSPORTS

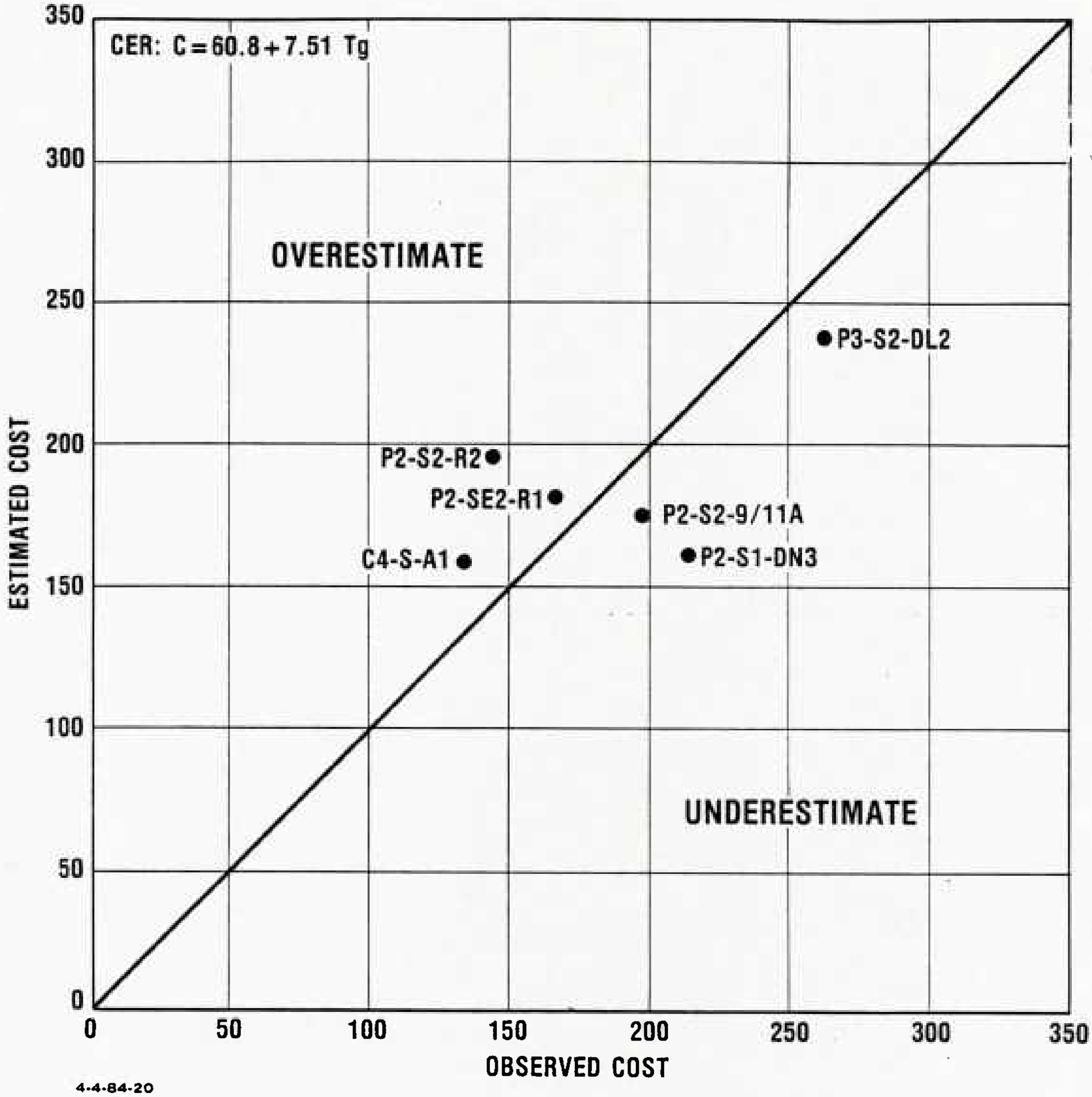

Figure 9. ESTIMATED VERSUS OBSERVED PROCUREMENT COST FOR PASSENGER SHIPS/TRANSPORTS

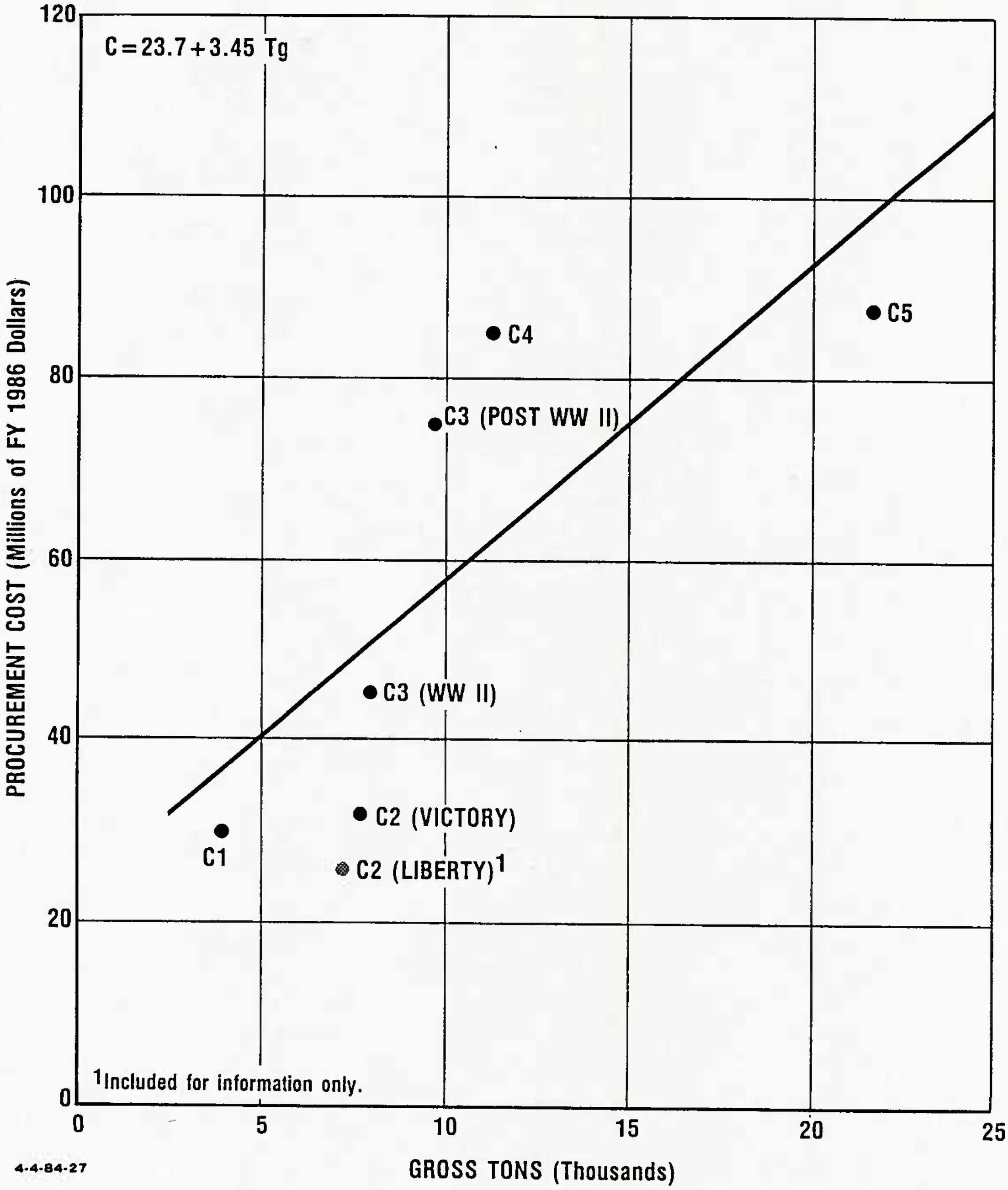

Figure 10. PROCUREMENT COST VERSUS GROSS TONNAGE CURVE FOR DRY CARGO SHIPS

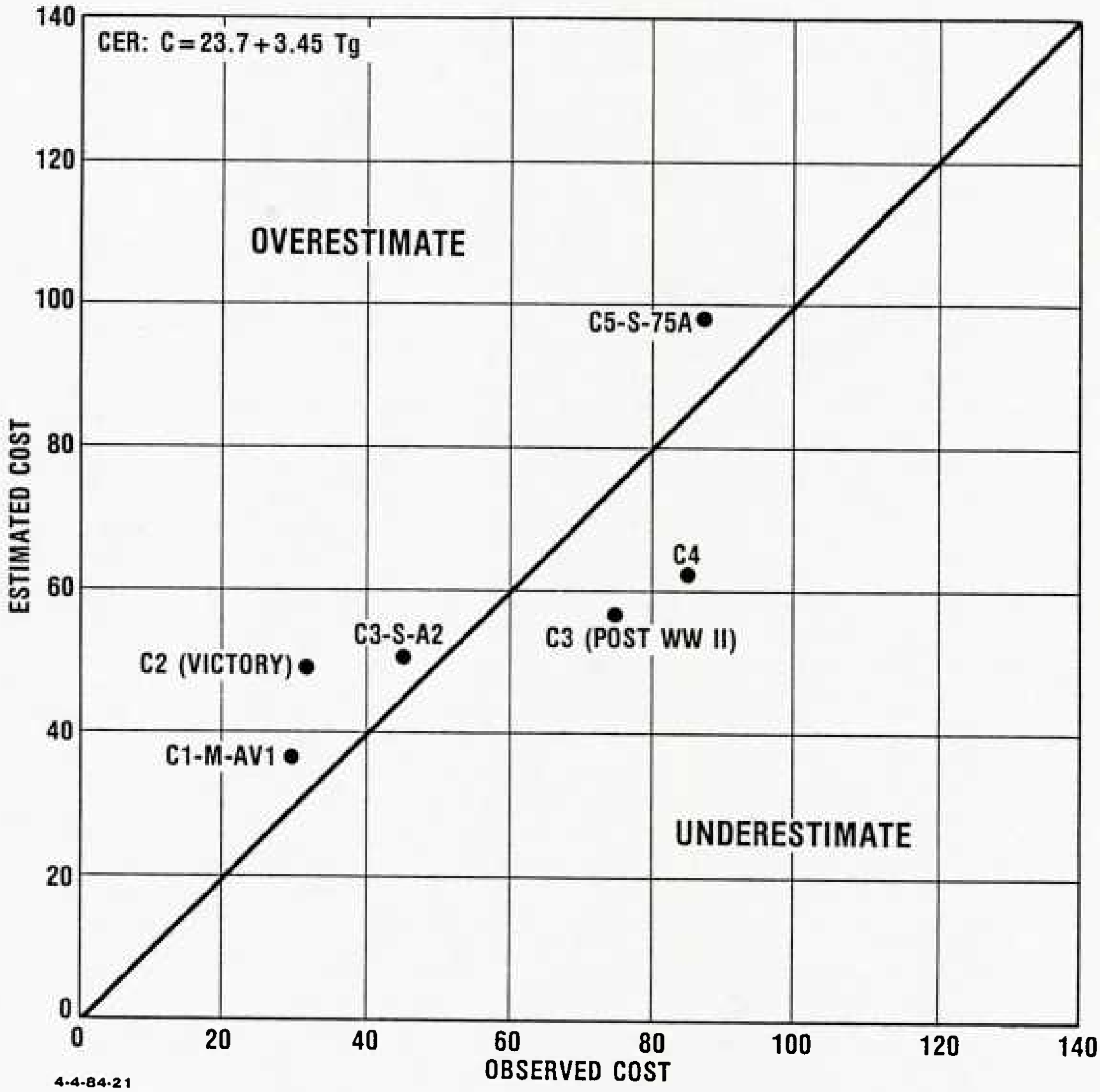

Figure 11. ESTIMATED VERSUS OBSERVED PROCUREMENT COST FOR DRY CARGO SHIPS

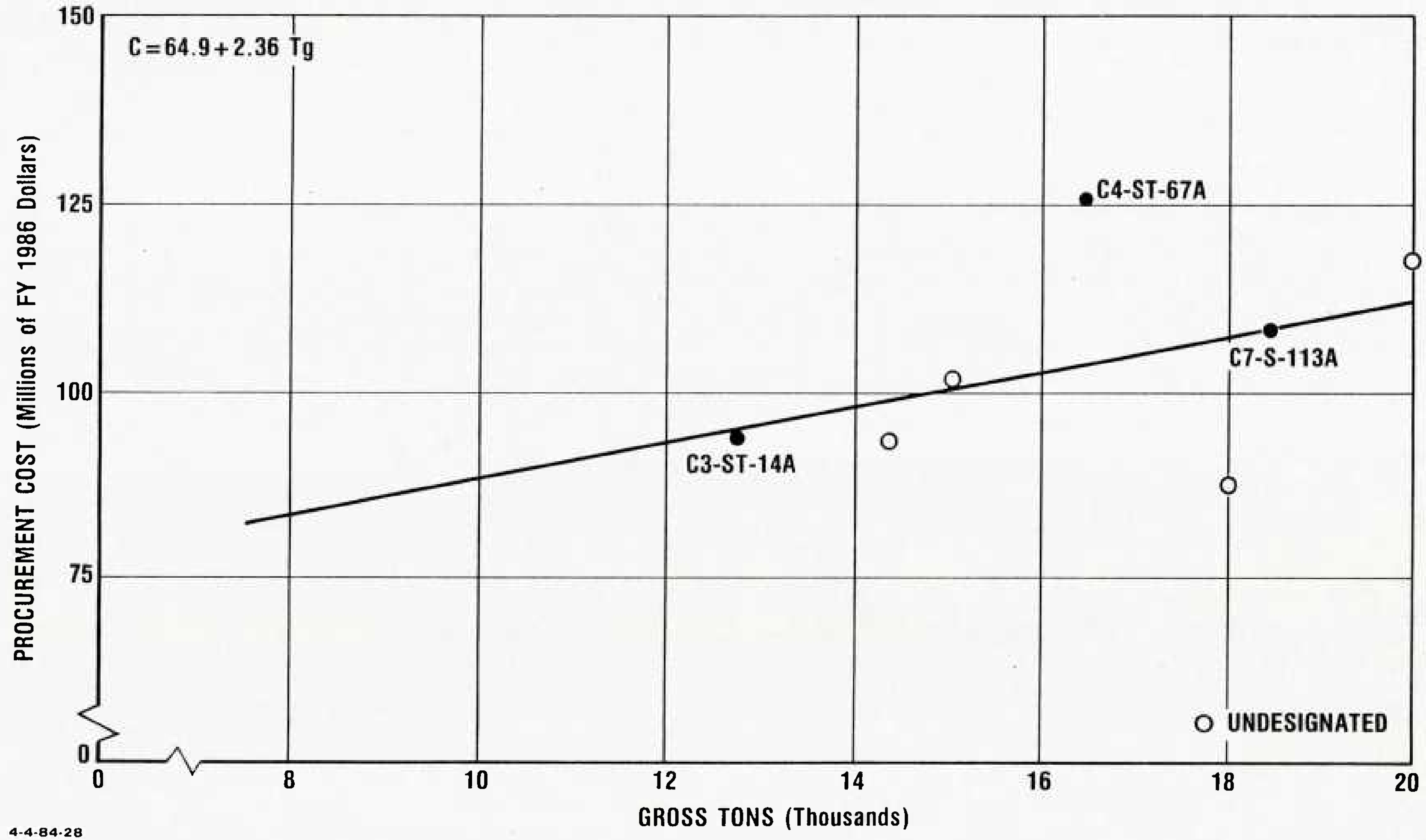

Figure 12. PROCUREMENT COST VERSUS GROSS TONNAGE CURVE FOR ROLL-ON/ROLL-OFF SHIPS

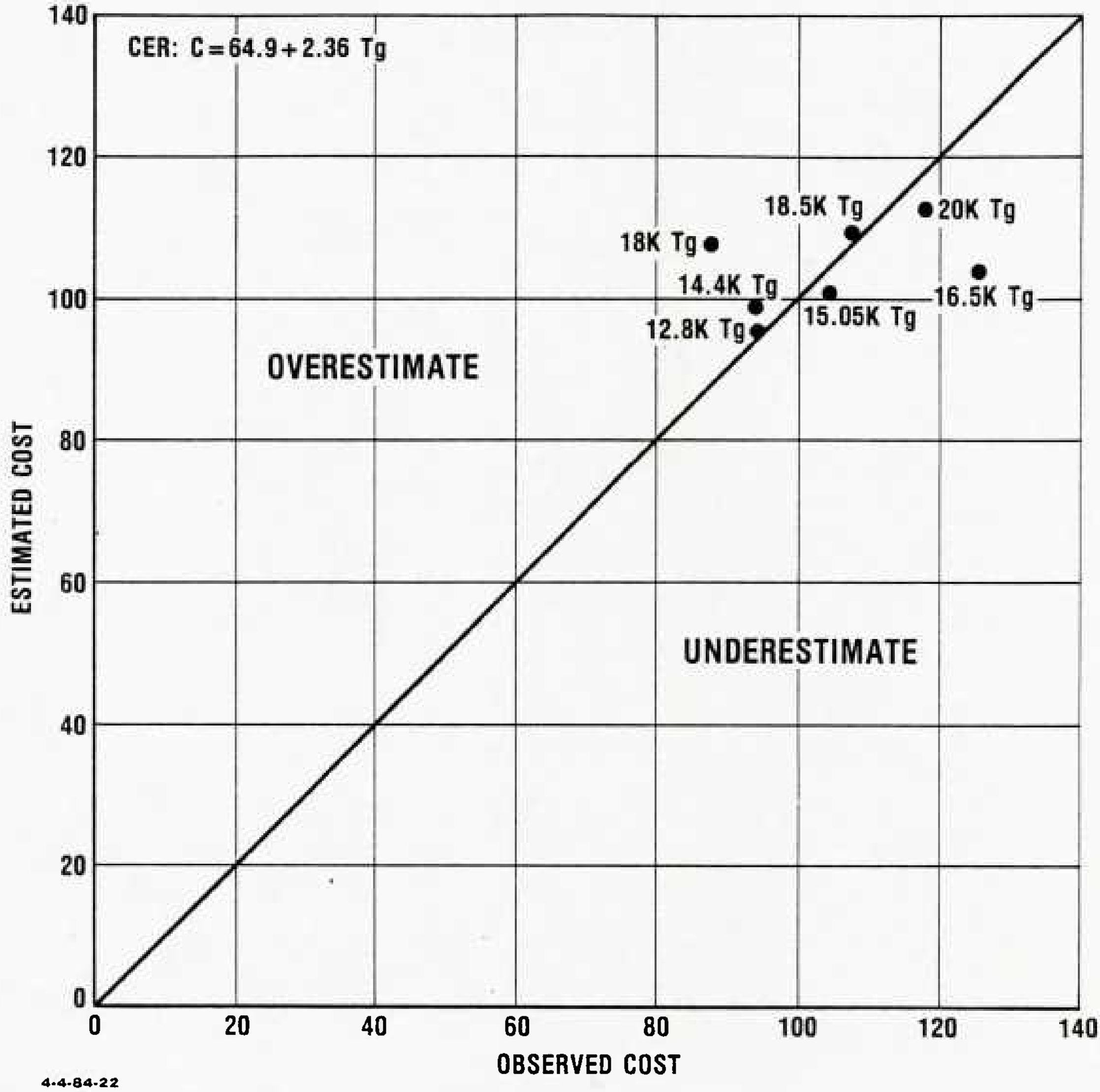

Figure 13. ESTIMATED VERSUS OBSERVED PROCUREMENT COST FOR ROLL-ON/ROLL-OFF SHIPS

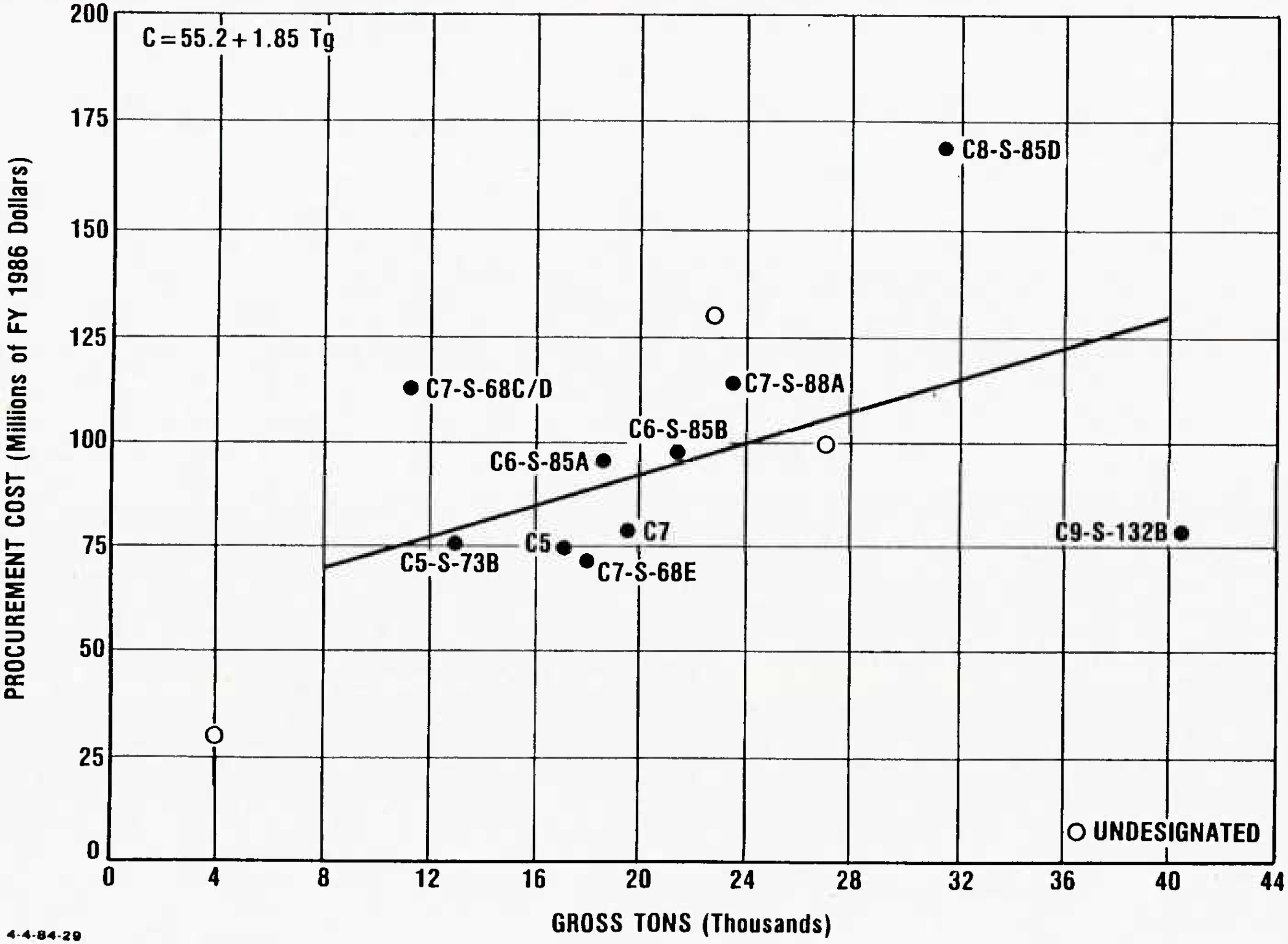

Figure 14. PROCUREMENT COST VERSUS GROSS TONNAGE CURVE FOR CONTAINER SHIPS

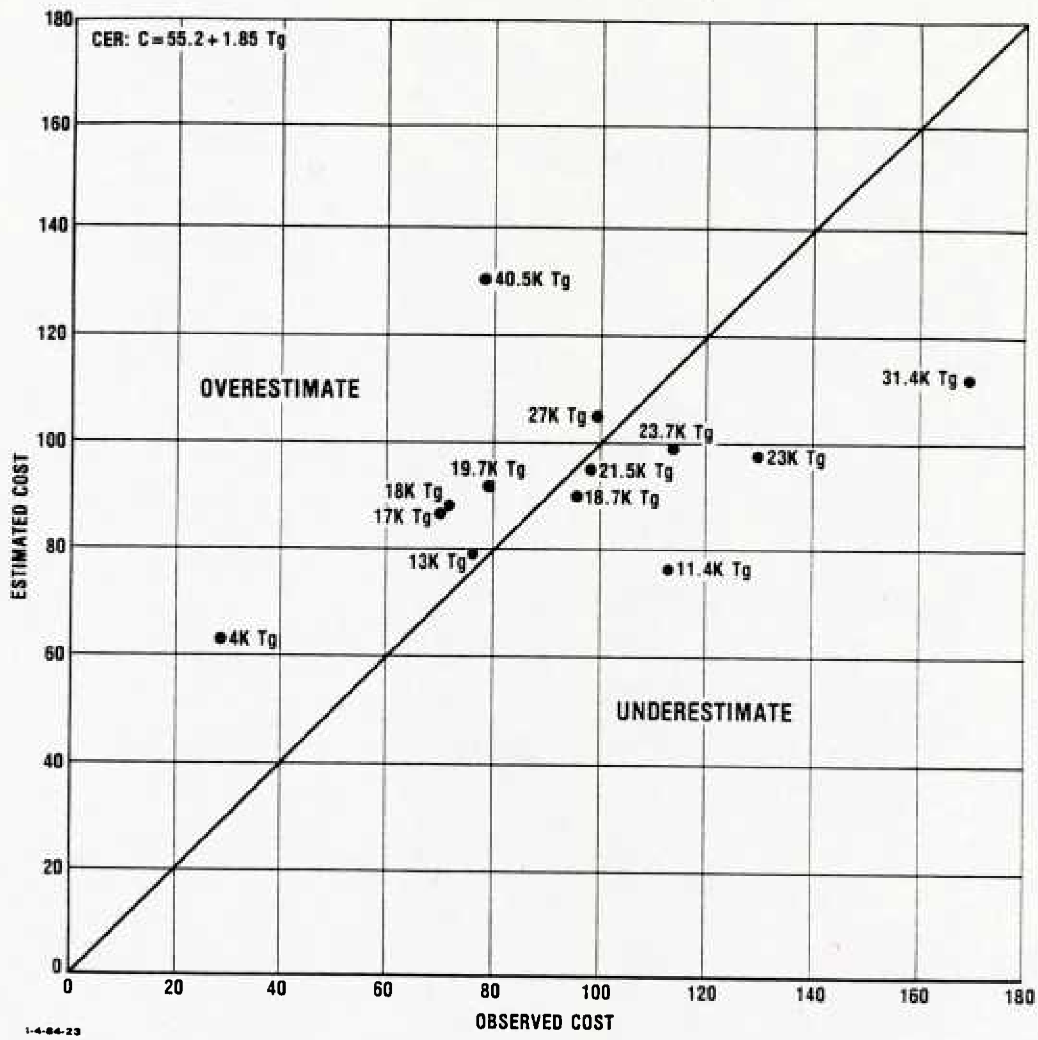

Figure 15. ESTIMATED VERSUS OBSERVED PROCUREMENT COST FOR CONTAINER SHIPS

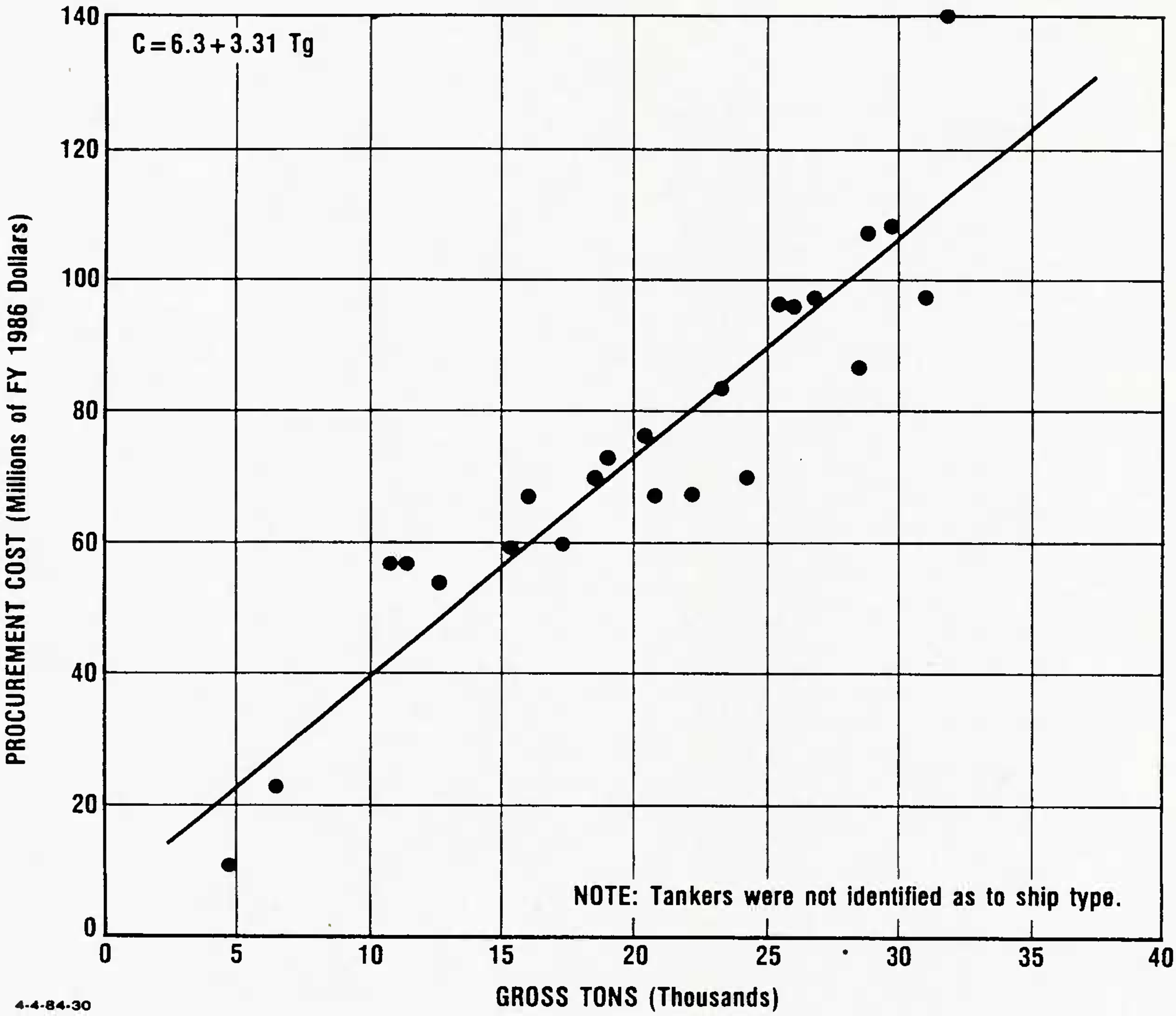

Figure 16. PROCUREMENT COST VERSUS GROSS TONNAGE CURVE FOR TANKERS

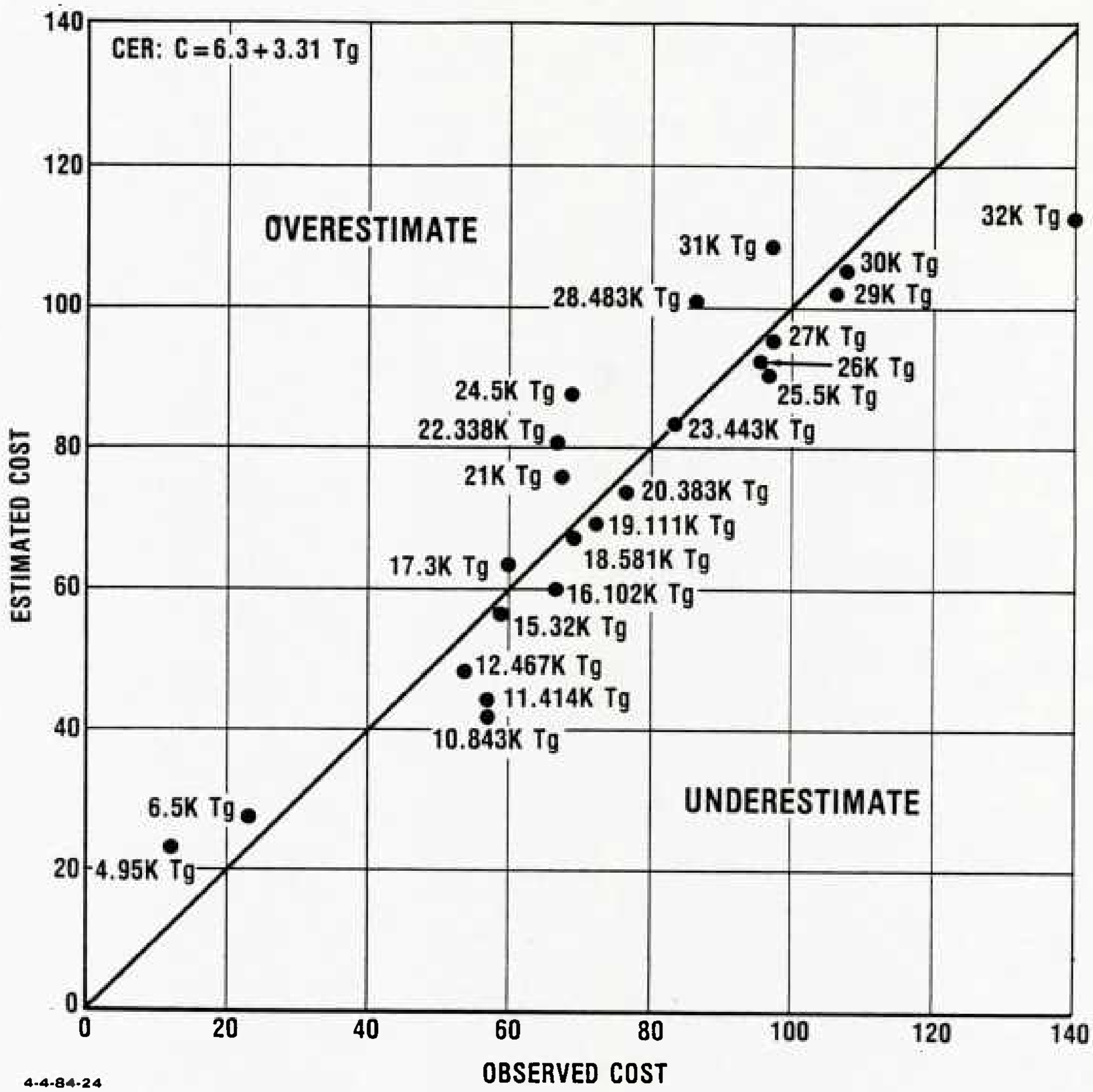

Figure 17. ESTIMATED VERSUS OBSERVED PROCUREMENT COST FOR TANKERS

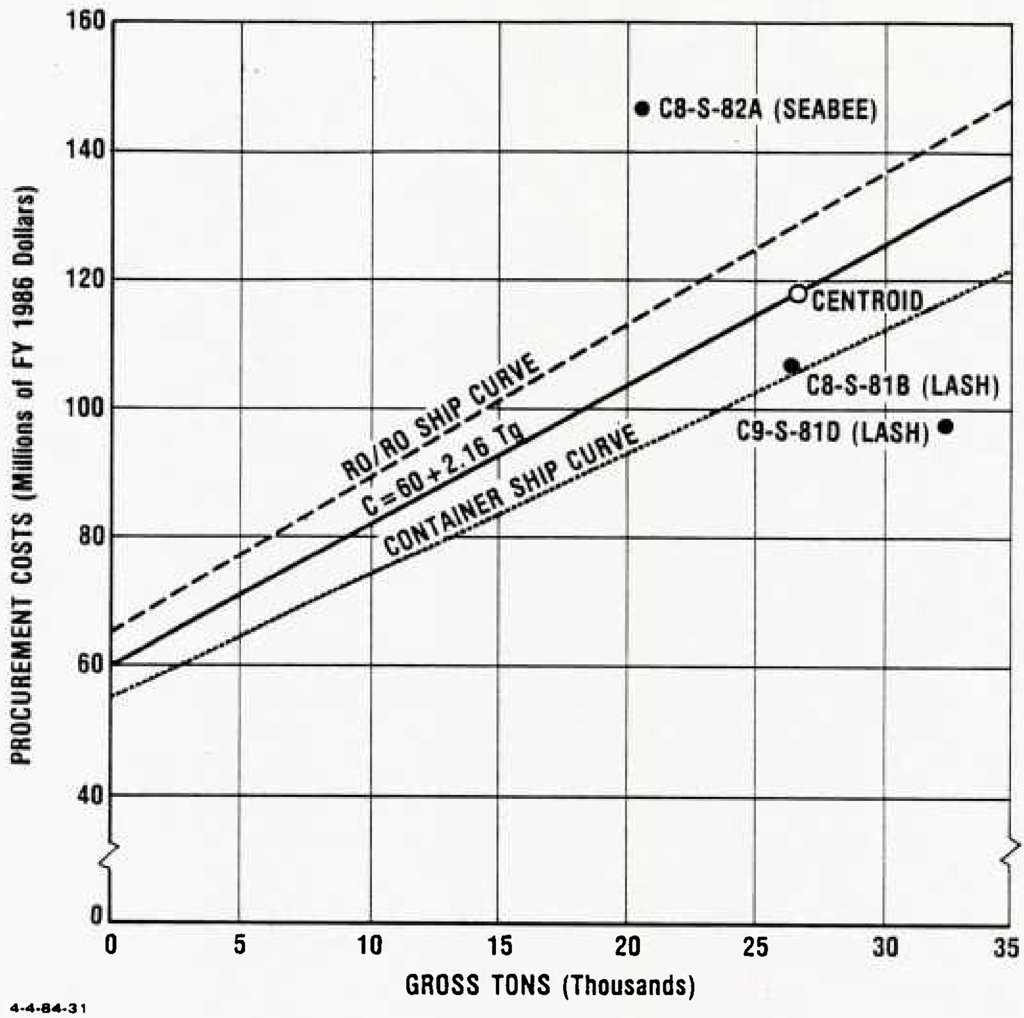

Figure 18. PROCUREMENT COST VERSUS GROSS TONNAGE FOR BARGE CARRYING SHIPS

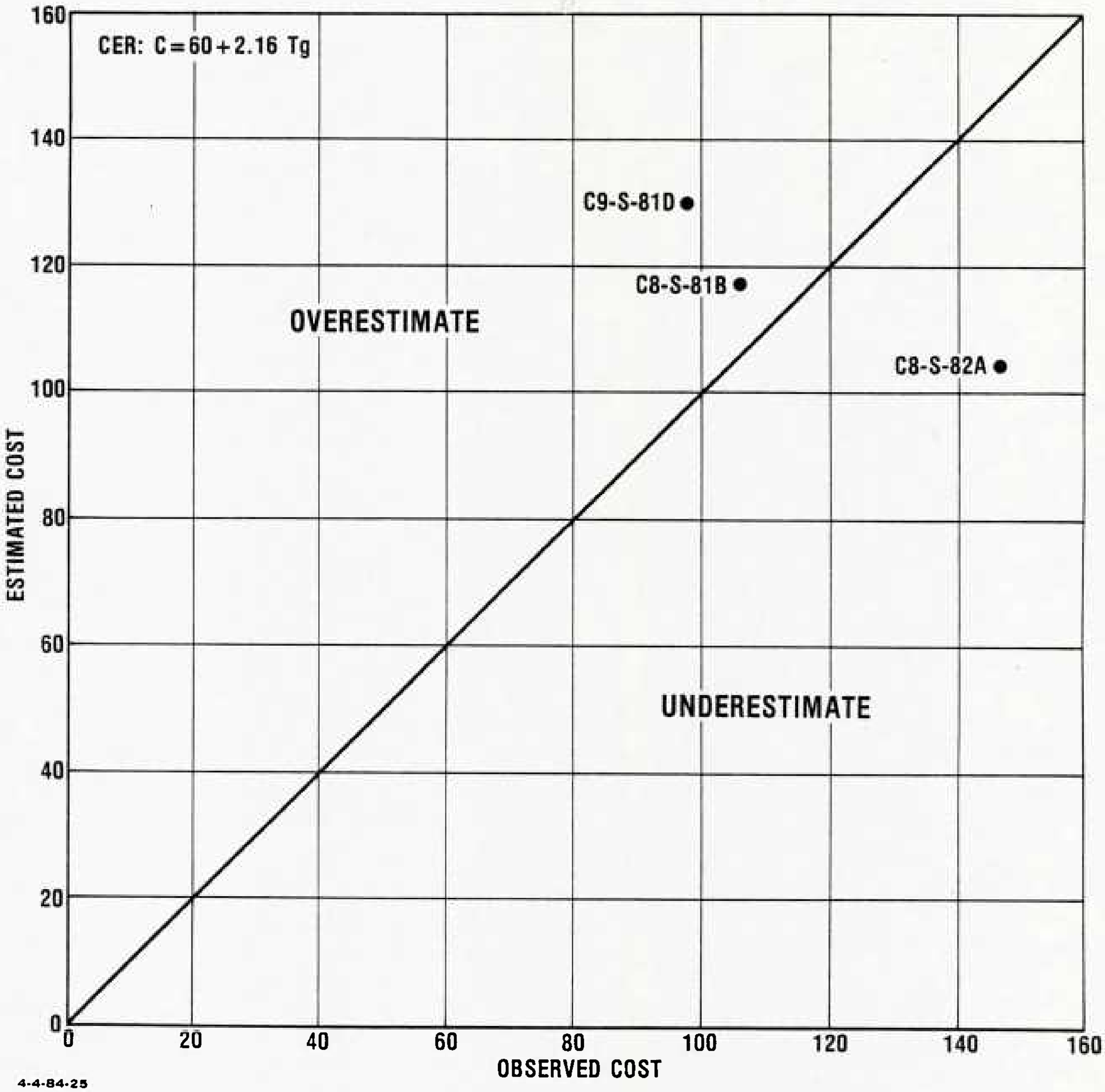

Figure 19. ESTIMATED VERSUS OBSERVED PROCUREMENT COST FOR BARGE CARRYING SHIPS

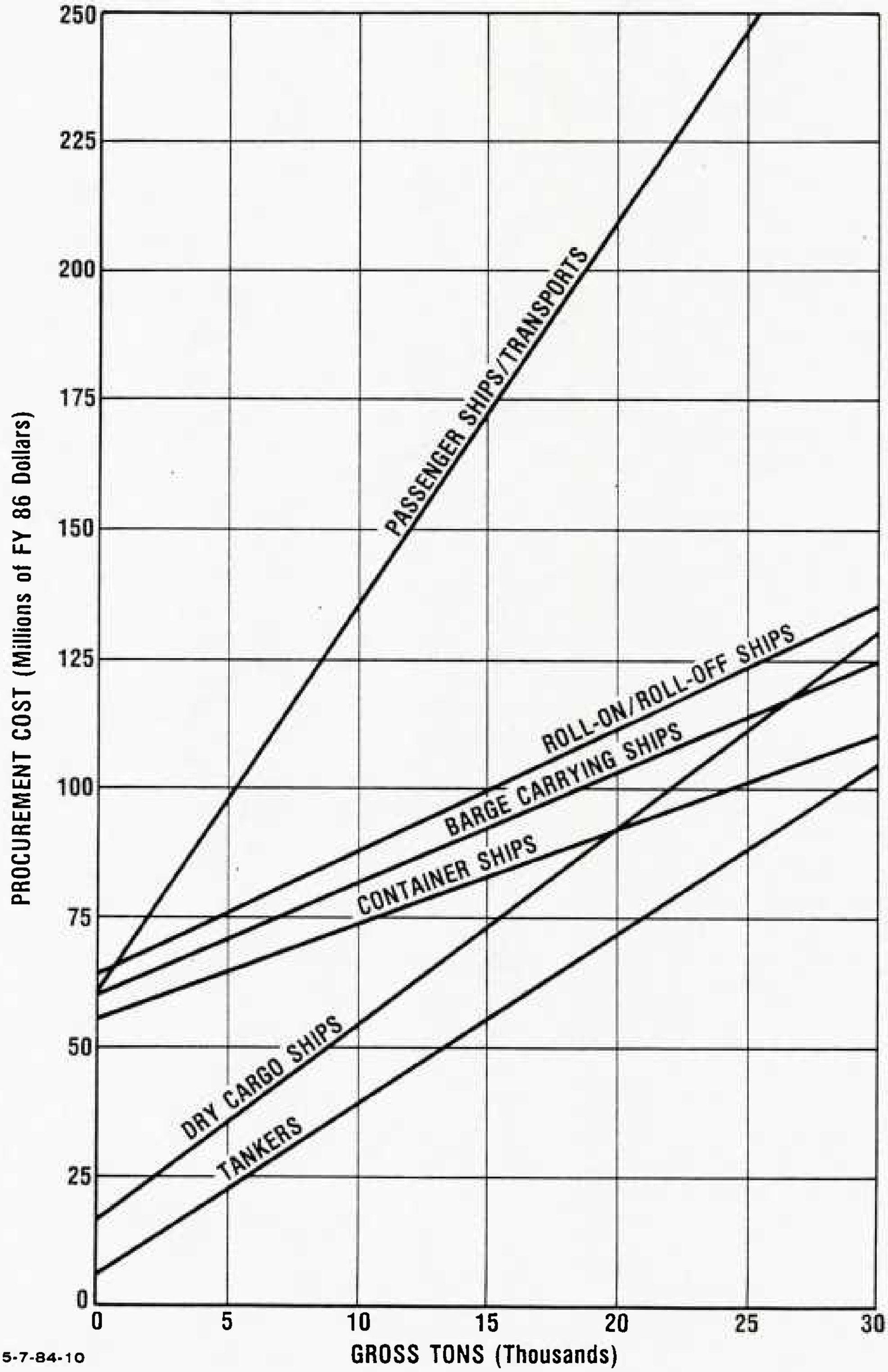

Figure 20. PROCUREMENT COST VERSUS GROSS TONNAGE FOR SIX CATEGORIES OF SHIPS

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